

Boussinesq Modeling of Alongshore Swash Zone Currents

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Award number: N00014-04-1-0310

LONG-TERM GOALS

The long-term goal of the study is to develop and integrate numerical models for the understanding and prediction of nearshore processes. The focus of the project is to develop the capability of modeling alongshore swash currents under field conditions based on Boussinesq-type formulations and field observations.

OBJECTIVES

The specific objectives of this project are to:

- Derive a complete set of fully nonlinear Boussinesq-type equations for waves and currents over a permeable beach, including the swash zone.
- Extend the two-dimensional, phase-resolving Boussinesq wave model to the swash zone with an emphasis on alongshore swash motions.
- Integrate the extended model with field data to gain insight into alongshore swash currents, including the correlation between the swash motions and the energetic shear waves, the partitioning of the irrotational (dispersive) and vortical (non-dispersive) motions in the swash zone, and the response of alongshore swash zone currents to the directionality and frequency spreading of offshore wave conditions.

APPROACH

The study involves theoretical formulation, model development and verification, and integration with field observations of swash motions. The starting point of the theoretical formulation is the Euler equation of motion for waves and currents above the permeable seabed and the locally-averaged Navier-Stokes equations for the flow inside the porous layer. A complete set of fully nonlinear Boussinesq-type equations for waves and currents over a permeable beach will be developed. Particular attention will be paid to the conservation property of potential vorticity and poor performance of existing equations when the ratio of the porous layer thickness to the water depth is large. Stokes-type analyses will be carried out to examine the dispersion and damping properties of the new set of equations.

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE 30 SEP 2005		2. REPORT TYPE		3. DATES COVERED 00-00-2005 to 00-00-2005	
4. TITLE AND SUBTITLE Boussinesq Modeling of Alongshore Swash Zone Currents			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of South Alabama, Department of Civil Engineering, Mobile, AL, 36688			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

One of the numerical problems associated with the simulation of swash motions is the requirement of very fine resolution in the swash zone in order to resolve the steep bore front and to prevent numerical instabilities caused by the moving shoreline. A conventional rectangular grid mesh covering a littoral area usually has difficulty to provide enough resolution in the surf and swash zone because of the computational restraint. We will employ the method of transforming the Boussinesq equations derived in a Cartesian coordinate system to the generalized curvilinear coordinates, as shown in Shi et al. (2001), to solve the resolution problem. The transformation allows for varying the grid spacing to give fine enough resolution in the swash zone and avoid over-resolving waves in the deep water. Furthermore, the small grid spacing in the swash zone permits the use of the wetting-drying method on a fixed grid for the treatment of a moving boundary. In addition, a time-dependent transformation of the coordinates will lead to a self-adaptive grid system (a moving grid) suitable for the simulation of swash motions. A comparison of different schemes for the moving boundary in the Boussinesq model will be made to determine the optimum technique with both good accuracy and efficiency for simulating cross-shore and alongshore velocities in the swash zone.

A close collaboration and interaction with field-oriented researchers on swash zone processes is one of the important components of this project. Field data collected by Dr. Britt Raubenheimer's research group at the Woods Hole Oceanographic Institute (WHOI) and Dr. Todd Holland's research group at the Naval Research Laboratory (NRL) will be utilized to verify the Boussinesq model with respect to wave runup and swash motion on beaches. The datasets include in-situ sensor array measurements and video-based observations. The verified Boussinesq model capable of simulating the swash motion on irregular beach topography will become available for the collaborators to study alongshore swash zone currents and allow for the development of hypotheses to be evaluated in future field experiments.

WORK COMPLETED

First, we have derived a new set of Boussinesq-type equations for nonlinear waves and surf-zone currents over a permeable beach (Chen 2005). A Stokes-type analysis and rational expansions have been carried out to examine the fundamental damping and dispersion properties of the new set of equations (Cruz and Chen 2005a). The vortical properties of the new and pre-existing Boussinesq equations have been carefully investigated. Second, numerical implementation of porous effects into a one-dimensional Boussinesq wave model has been completed. Preliminary results have been documented in Cruz and Chen (2004). We have been testing the numerical model against laboratory experiments on wave transformation and breaking over porous beds and documenting the results into a manuscript (Cruz and Chen 2005b). Third, efforts have been devoted to the testing of the curvilinear Boussinesq wave model, FUNWAVE 2.0 with respect to swash motions. We have examined three different schemes for the treatment of a moving shoreline with an emphasis on the swash velocity.

RESULTS

The major results obtained so far are: 1) the development of a complete set of Boussinesq-type equations suitable for water waves and wave-induced nearshore circulation over an inhomogeneous, permeable seabed, and 2) the implementation and testing of the numerical models. We developed a new approach to eliminating the z -dependency in the Boussinesq-type equations. This technique allows for the existence and advection of the vertical vorticity component in the flow field with the accuracy consistent with the level of approximation in the Boussinesq-type equations for the pure wave motion.

Pre-existing Boussinesq-type equations perform poorly when the thickness of the porous layer is several times larger than the water depth. We reexamined the scaling of the resistance force and revealed the significance of the vertical velocity to the pressure field in the porous layer. This led to the retention of higher-order terms associated with the damping in the momentum equations. An analysis of the vortical property of the resultant equations indicates that the energy dissipation in the porous layer can serve as a source of vertical vorticity up to the leading order. The equations retain the conservation of potential vorticity up to $O(\mu^2)$, where μ is the measure the frequency dispersion. Such a property is desirable for modeling wave-induced surf zone currents. Moreover, the procedure of consistently recovering the vertical vorticity and eliminating the z -dependency can be used to extend a variety of Boussinesq-type equations originally derived for potential flows to quasi-rotational wave-current motions in the nearshore (Chen 2005).

A Stokes-type analysis and rational expansions were carried out to extract the fundamental properties from the complex Boussinesq equations. The linear dispersion relationship and the damping rate owing to the porous layers were compared with the exact solutions for linear waves over a homogeneous, porous, flat bottom. We developed a new optimization technique to determine the two model parameters for the new equations. The new procedure has been extended to realistic bottom topography, allowing for variations of the model parameters to account for spatial variations of bottom permeability and porous-layer thickness. We have developed a Boussinesq model for nonlinear waves propagating over porous beds (Cruz and Chen 2005b).

Figure 1 shows a comparison of the modeled wave profiles on an impermeable bed (solid line) and over a permeable (red dotted line) layer of coarse sand. It is seen that the porous damping results in smaller wave height and weaker higher harmonics than does the impermeable sloping bottom. However, the wave celerity, or wave length is hardly influenced by the porous layer during wave shoaling. On the horizontal bed, the waves over the solid bottom are slightly faster than the waves over the porous bed because of the accelerating effects of wave nonlinearity and wave breaking.

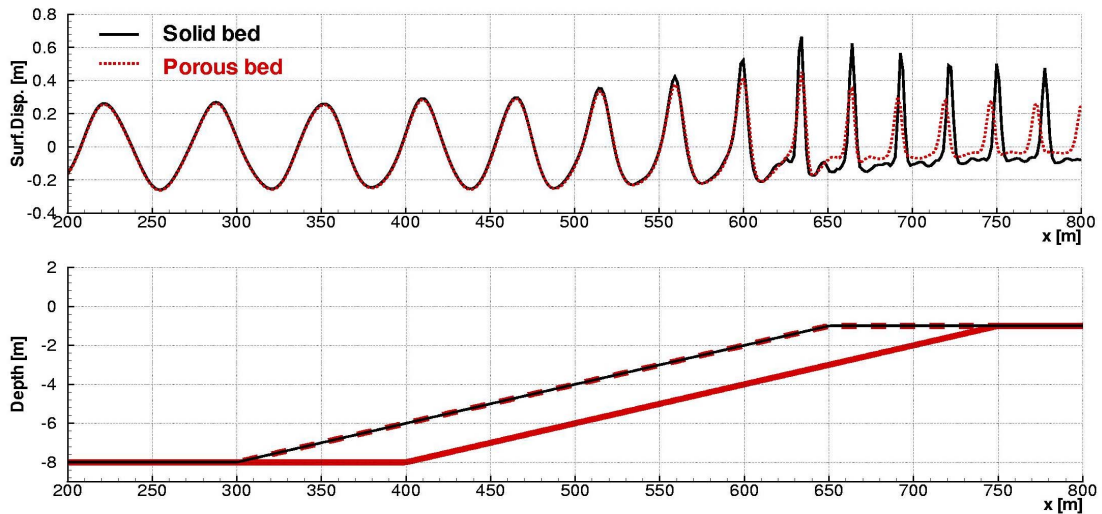


Figure 1: Comparison of modeled wave profiles on an impermeable bed (solid line) and over a permeable (red dotted line) layer of coarse sand. $H = 0.5$ m, $T = 8$ sec, the porous layer: $n = 0.40$, $d_{50} = 2$ mm.

The numerical model was tested against the analytical solution of linear waves on a horizontal, homogenous porous bed. Excellent agreement has been found. To verify the model accuracy for nonlinear waves propagating over uneven porous beds, the model is further tested using laboratory data. Figure 2 shows a model and data comparison. The top panel depicts the wave envelope and a snapshot of the computed free surface elevation over a porous sill. The grain size is 6.7 mm and the porosity is 0.44. It is seen in the middle panel that the computed wave heights are in good agreement with the laboratory measurement at eight gage stations.

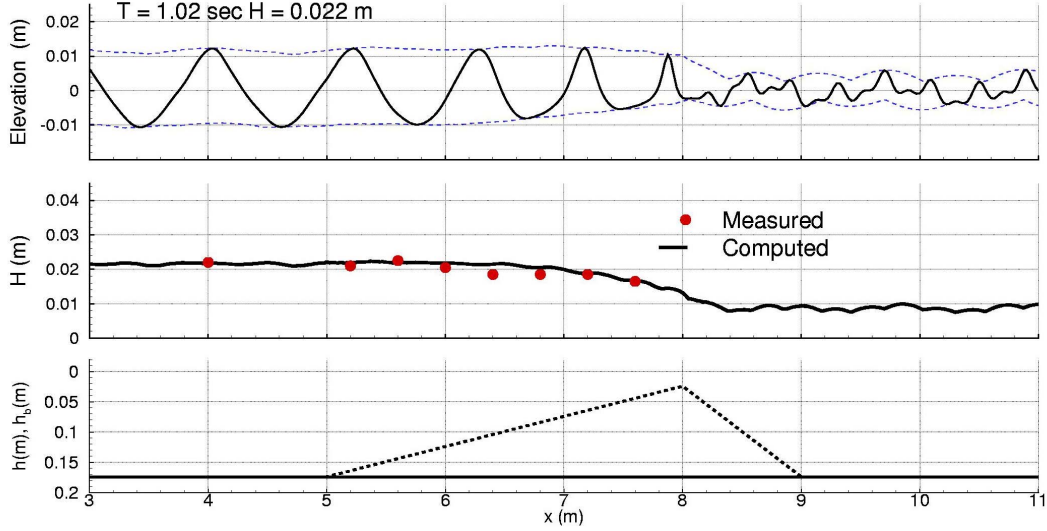


Figure 2: Model and data comparison of wave transformation over a porous sill on an impermeable flat bottom. Solid lines: computational results. Red dotted line: laboratory measurements.
 $H = 0.022 \text{ m}$, $T = 1.02 \text{ sec}$, porous sill: $n = 0.44$, $d_{50} = 6.7 \text{ mm}$.

The fully nonlinear Boussinesq model on generalized curvilinear coordinates, FUNWAVE 2.0, is a component of the nearshore modeling package, NearCoM. We have adopted FUNWAVE 2.0 as the platform for modeling alongshore swash currents. Three numerical schemes for the treatment of a moving shoreline have been tested in the framework of FUNWAVE 2.0. They are the slotted-beach technique for wave runup, the thin-film method used in coastal ocean and estuarine circulation models for the treatment of tidal flats (Oey 2005), and the wetting and drying scheme using linear extrapolation (Lynett and Liu 2002). It turns out that the current version of FUNWAVE 2.0 incorporating the slotted-beach technique is not able to correctly model the swash velocity owing to numerical instabilities when small slot width is used. A better-devised numerical filtering scheme is needed to stabilize the narrow slotted-beach scheme in the swash zone.

We have tested the model using the analytical solution of long wave runup on a sloping bottom (Carrier and Greenspan, 1958). Figure 3 shows the comparison of the numerical (black lines) and exact (red lines) solutions of the free surface profiles and velocity profiles. It is seen in the left panel that the wetting-drying scheme we have implemented into FUNWAVE 2.0 is able to accurately reproduce Carrier and Greenspan's analytical solution, including the maximum swash excursion, and the nodes and anti-nodes of the standing waves. More importantly, the modeled swash velocities are in excellent agreement with the exact solution, as seen in the right panel.

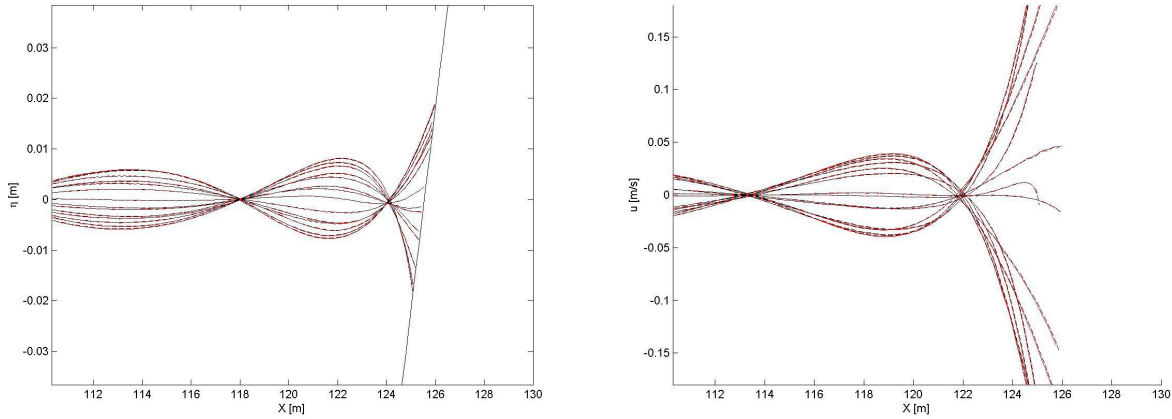


Figure 3: Comparison of numerical (black lines) and analytical (red lines) solutions of long wave runoff on a sloping bottom. Left: free surface profiles. Right: velocity profiles.

In addition to the theoretical and numerical results summarized above, we have communicated with Dr. Britt Raubenheimer at WHOI and received the SWASHX data to be used to test the Boussinesq model extended to the swash zone.

IMPACT/APPLICATIONS

The proposed research is expected to improve the capability of modeling swash zone processes. First, the study will extend the applicability of Boussinesq models (Chen et al., 1999, and Chen et al., 2003) to the swash zone and permeable beds. This will provide sediment transport models with more realistic estimates of cross-shore and alongshore velocities in the swash zone. Therefore, improvements in predicting sediment transport in the swash zone are anticipated. Second, the complex nature of nearshore processes calls for the integration of numerical models with field measurements in our research. The extended model will become available for researchers at the NRL and other institutions to complement their field study of swash zone processes, including alongshore swash zone currents measured in the NCEX. In addition, it is anticipated that the proposed project will also complement the NOPP project led by Dr. Jim Kirby to develop and verify a community model for nearshore processes. The phase-resolving Boussinesq model with extension to the swash zone will provide the phase-averaged wave and current models being developed in the NOPP project with useful information about the swash motion and the shoreline boundary conditions. The results will give new insight into alongshore swash zone currents. In addition, the Boussinesq model for irregular waves propagating over porous beds is useful for the MURI study on remote sensing of seabed properties.

TRANSITIONS

The complete set of Boussinesq equations for nonlinear waves and surf zone currents has been shared with the NOPP researchers. As a result, the second-order vertical component of the vorticity vector on an impermeable bed has been implemented into the Boussinesq wave model, FUNWAVE, at the University of Delaware. In addition, Dr. James Kaihatu at the NRL has expressed interest in the Boussinesq model for wave transformation on heterogeneous porous seabed.

RELATED PROJECTS

The field observations of cross-shore and alongshore swash-zone fluid velocities by Dr. Britt Raubenheimer at the WOHI will be utilized to verify our numerical models.

Dr. K. Todd Holland at the NRL is leading the study of nearshore processes on heterogeneous beaches. Integration of our models with his field observations is planned.

ONR had recently released a BAA of a MURI dealing with the inversion of free surface information to infer the bottom sediment composition. The Boussinesq wave model extended to porous beds can be used to complement the study.

The development of the numerical models has been partially supported by the Federal Highway Administration through the study of storm wave transformation over inundated coastal roadways.

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